SYSTEM AND METHOD FOR WIRELESS SIGNAL TIME OF ARRIVAL

BACKGROUND OF THE INVENTION

Related Applications

[0001] This application claims priority to U.S. Provisional Application No. 60/340,189
5   filed on December 14, 2001.

Field of the Invention

[0002] The present invention is directed generally to time of arrival estimation and, more particularly, to a system and method for mathematical modeling of a function
10   indicative of time of arrival.

Description of the Related Art

[0003] Existing position location technologies based on global positioning system (GPS) use a network of satellites in the sky which transmit signals at a known time. A
15   GPS receiver on the ground measures the time of arrival of the signals from each satellite it can detect. The time of arrival, along with the exact location of the satellites and the exact time the signal was transmitted from each satellite is used to triangulate the position of the GPS receiver. A typical GPS receiver requires four satellites to make a triangulation, and the performance of the resulting calculation increases as the
20   number of satellites that can be detected increases.

[0004] In an alternative to GPS, an existing network of cellular base stations can be treated as a network of satellites for purposes of position location. Similar to GPS technology, the exact location of each base station, the exact time at which the base station is transmitting a signal, and the time of arrival of the base station signal at a
25   mobile station can be used to triangulate the position of the mobile station. This technique is described by some service providers as advanced forward link trilateration (AFLT). Wireless networks may also be used in conjunction with GPS to determine the location of the mobile station.

[0005] A significant problem faced by the mobile station is to measure the time of arrival of the signals that are received from each base station. Different wireless technologies may take different approaches to time of arrival measurements. Code division multiple access (CDMA) is one such technology. CDMA modulation is one of several techniques that allow a large number of system users to share a communication system. It is possible to utilize conventional CDMA modulation techniques as part of an AFLT system.

[0006] CDMA modulation techniques are disclosed in United States Patent No. 4,901,307, issued on February 13, 1990, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," which is assigned to the assignee of the present invention, and the disclosure of which is incorporated herein by reference. The above-referenced patent discloses the use of a phase-coherent and chip-synchronous chip sequence that is defined as a pilot chip sequence, or pilot signal. The pilot signal can be used to provide phase and time acquisition and tracking, and multi-path correction.

[0007] Methods for acquiring the pilot signals are disclosed in the above-referenced patent and in the following patents: (1) United States Patent No. 5,781,543, issued on July 14, 1998 and entitled "POWER-EFFICIENT ACQUISITION OF A CDMA PILOT SIGNAL;" and (2) United States Patent No. 5,805,648, issued on September 8, 1998 and entitled "METHOD AND APPARATUS FOR PERFORMING SEARCH ACQUISITION IN A CDMA COMMUNICATION SYSTEM," both of which are assigned to the assignee of the present invention and the disclosures thereof are incorporated herein by reference.

[0008] When the wireless communication device is first powered on, the device must establish a communication link with a base transceiver station (BTS). The wireless communication device will typically receive pilot signals from a plurality of BTSs. The wireless device will search for the signals from the BTSs and will establish a communication link with a selected BTS to permit the reception and transmission of data, such as audio signals, over the established communication link. The selection of a particular BTS and the actual communication between the wireless communication

device and the selected BTS are well known in the art and need not be discussed in detail herein.

[0009] As discussed in the above-referenced patents, each BTS broadcasts the same pseudo-noise (PN) code pilot signal, but with a different time offset.

5   [0010] To acquire the pilot signal, the wireless device must synchronize with the time offset and frequency of the signal transmitted by a BTS. The object of a "searcher" process in the wireless device is to find the time offset of the received signal. The searcher uses an estimated frequency. If the estimated frequency is not sufficiently close to the frequency of the pilot signal, the received signal will not be acquired.

10   [0011] When a BTS is properly detected, the output of the searcher is a pulse, which may be considered a correlation pulse. This correlation pulse may be used to measure the time of arrival of the signal from the BTS. However, the accuracy of such time of arrival measurements severely limits the accuracy of the position determination. Therefore, it can be appreciated that there is a significant need for an improved system

15   for estimating time of arrival that increases the accuracy of the position determining process. The present invention provides this and other advantages, as will be apparent from the following detailed description and accompanying figures.

BRIEF SUMMARY OF THE INVENTION

[0012] The present invention is embodied in a system and method for accurately

20   determining time of arrival of signals in a wireless communication system. In an exemplary embodiment, the system comprises a searcher to analyze received signals and to determine therefrom a correlation signal level at predetermined points in time. The searcher determines a maximum signal level at a selected one of the predetermined points in time. A modeling processor generates a mathematical model of a

25   predetermined response function using the maximum signal level and correlation signal levels from predetermined points in time adjacent the selected time. The modeling processor uses the mathematical model to determine a time associated with a peak correlation signal level.

[0013] In one embodiment, the correlation signal levels are based on received signal strength of the received signals. The maximum signal level in correlation signal levels from predetermined points in time adjacent the selected time may be used to determine coefficients in the mathematical model. In one embodiment thereof, the coefficients in the mathematical model are used to determine a time associate with a peak value of the mathematical model.

[0014] In one embodiment, the mathematical model is a second-order mathematical function. The second-order mathematical function may have three coefficients, the maximum signal level and two correlation signal levels from predetermined points in time adjacent the selected time being used to determine the three coefficients in the second-order mathematical model. Alternatively, a mathematical model greater than a second-order mathematical model may be used.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0015] FIG. 1 is a block diagram illustrating a mobile unit and established communication links with a plurality of base transceiver stations (BTSs).

[0016] FIG. 2 is a functional block diagram of a mobile unit implementing the present invention.

[0017] FIG. 3 is a waveform illustrating the detection of a signal from a BTS.

[0018] FIG. 4 is a waveform illustrating the detection of a signal from a BTS using a higher resolution than the waveform in FIG. 3.

[0019] FIG. 5 is a waveform illustrating a modeling function used by the present invention to more accurately determine the time of arrival.

[0020] FIG. 6 is a flowchart illustrating the operation of the system of FIG. 2.

DETAILED DESCRIPTION OF THE INVENTION

[0021] The present invention uses a mathematical modeling technique to more accurately determine the time of arrival of the signal transmitted from a base transceiver

station (BTS). FIG. 1 is a diagram illustrating the operation of a wireless system using advanced forward link trilateration (AFLT) to determine the location of the wireless unit. As illustrated in FIG. 1, a wireless unit **10** is within range of a plurality of BTSs **12-18**. To permit normal communication, such as voice communication, the wireless

5 unit **10** establishes communication links **20-26** with the BTSs **12-18**, respectively. The information derived in the process of establishing the communication links **20-26** may be used to estimate the time of arrival and thereby determine the location of the wireless unit **10** with respect to the BTSs **12-18**. It should be noted that it is not necessary to establish communications with a BTS to measure its time of arrival. The wireless unit

10 **10** can actually measure the time of arrival by simply listening to all the base stations. However, the data typically generated within the wireless unit **10** is not sufficiently accurate to determine the precise location of the wireless unit **10**. The present invention derives more accurate time of arrival data that may be used to more precisely determine the location of the wireless unit **10**.

15 **[0022]** The present invention is embodied in a system **100** illustrated in the functional block diagram of FIG. 2. The system **100** includes a central processing unit (CPU) **102**, which controls operation of the system. Those skilled in the art will appreciate that the CPU **102** is intended to encompass any processing device capable of operating the telecommunication system. This includes microprocessors, embedded controllers,

20 application specific integrated circuits (ASICs), digital signal processors (DSPs), state machines, dedicated discrete hardware, and the like. The present invention is not limited by the specific hardware component selected to implement the CPU **102**.

[0023] The system also preferably includes a memory **104**, which may include both read-only memory (ROM) and random access memory (RAM). The memory **104**

25 provides instructions and data to the CPU **102**. A portion of the memory **104** may also include non-volatile random access memory (NVRAM).

[0024] The system **100**, which is typically embodied in a wireless communication device such as a cellular telephone, also includes a housing **106** that contains a transmitter **108** and a receiver **110** to allow transmission and reception of data, such as

30 audio communications, between the system **100** and a remote location, such as a BTS

(*e.g.*, the BTS **12** of FIG. 1. The transmitter **108** and receiver **110** may be combined into a transceiver **112**. An antenna **114** is attached to the housing **106** and electrically coupled to the transceiver **112**. The operation of the transmitter **108**, receiver **110**, and antenna **114** is well known in the art and need not be described herein except as it

5   relates specifically to the present invention.

[0025] In an implementation for a CDMA device, the system also includes a searcher **116** to detect and quantify the level of signals received by the receiver **110**. The searcher **116** detects one or more parameters, such as a total energy, pilot energy per pseudo noise (PN) chip, power spectral density, and other parameters, as is known in

10   the art. As will be described in greater detail, the searcher **116** performs a correlation analysis to determine time of arrival (TOA) from a location, such as the BTS **14** (see FIG. 1).

[0026] The searcher **116** performs a correlation analysis between a reference signal and a received signal and generates a correlation output signal. A signal analyzer or

15   modeling processor **120** analyzes the correlation signals and uses a mathematical model **122** to generate accurate TOA data.

[0027] The system **100** includes a timer **124** to provide system timing that is used to measure delay times in the arrival of signals from different sources (*e.g.*, the BTSs **12-18**). The timer **124** may be a stand-alone device or part of the CPU **102**.

20   [0028] The various components of the system **100** are coupled together by a bus system **126**, which may include a power bus, a control signal bus, and a status signal bus in addition to a data bus. However, for the sake of clarity, the various buses are illustrated in FIG. 2 as the bus system **126**.

[0029] One skilled in the art will appreciate that the system **100** illustrated in FIG. 2 is a

25   functional block diagram rather than a listing of specific components. For example, although the searcher **116** and signal analyzer **120** are illustrated as two separate blocks within the system **100**, they may be in fact embodied in one physical component, such as a digital signal processor (DSP). They may also reside as program codes in the memory **104**, such code being operated on by the CPU **102**. The same considerations

may apply to other components listed in the system **100** of FIG. 2, such as the timer **124**.

[0030] Operation of the components shown in the system **100** of FIG. 2 will be explained with reference to FIGs. 3-6. FIG. 3 is a waveform-timing diagram illustrating

5   examples of the correlation pulses generated by the searcher **116**. To assist in proper understanding of the present invention, a brief description of time of arrival processing using, by way of example, a CDMA mobile unit, will be presented. A mobile unit (*e.g.,* the mobile unit **10** in FIG. 1) implementing the system **100** of FIG. 2 is initially assigned a pseudo noise (PN) code. The PN code may be stored in the memory **104** as

10   a local reference. When a base station (*e.g.,* the BTS **12**) transmits data to the mobile unit **10**, the base station transmits the PN code. The system **100** continuously searches for a correlation between the local reference (*i.e.,* the stored PN code) and transmitted data (*i.e.,* the transmitted PN code).

[0031] As is well known in the art, all the transmitters (*e.g.,* the BTSs **12-18**) transmit

15   the same PN code, but the start of transmission of the PN code from the transmitter in each BTS is delayed in time by a precisely known offset. The time offsets are measured in multiples of 64 chips. As those skilled in the art will appreciate, a "chip" is a single piece of data in the PN sequence. Because the data is transmitted at a known rate, chips may be used as a measure of time. Although the present description may be

20   characterized in actual units of time, it is more convenient to refer to the time in terms of chips because the system **100** performs its analysis and measurements in terms of chips.

[0032] The PN offsets are selectively assigned to transmitters so that the offsets in a geographic region are spread out as much as possible to avoid interference between

25   transmitters. The transmitters (*e.g.,* the transmitters in the BTSs **12-18**) may be identified by transmitted identification data, but are sometimes labeled by their PN offset time. For example, the transmitter in BTS **12** may be identified as PN 300 to indicate that it transmits the PN code at an offset of 300. It should be understood, however, that regardless of how the transmitters are labeled, the relative offset of each

30   with respect to each other can be established from the information encoded in the

signals. The receiver **110** (see FIG. 2) in the mobile unit **10** will detect the PN from each of the transmitters in the geographic area (*e.g.*, the transmitters in the BTSs **12-18**).

[0033] The searcher **116** shifts the stored reference until a correlation is detected between the stored reference and the transmitted data. The degree of shift of the stored reference is selected to optimize the acquisition rate and provide sufficient synchronization between the wireless device **10** and a particular BTS (*e.g.*, the BTS **12** of FIG. 1). This is illustrated in the waveforms of FIGs. 3 and 4. In FIG. 3, the searcher **116** shifts the PN code one chip at a time. In the example illustrated in FIG. 3, a correlation waveform **140** has a maximum value at chip **2**.

[0034] A number of different measures, such as total energy, pilot energy per PN chip or power spectral density, may be used as the correlation value. One commonly used measure is simply the received signal strength such as may be indicated by the received signal strength index (RSSI). Those skilled in the art will recognize that the searcher **116** (see FIG. 1) produces numeric values related to the correlation between the stored PN code and the transmitted PN code. The waveform **140** results from plotting the correlation values from the searcher at different chip values.

[0035] The waveform **140** closely resembles the mathematical function

$$\frac{sin\ \pi x}{\pi x} \tag{1}$$

which may be used to accurately characterize the correlation function. This function is common in engineering and is sometimes referred to as a *sinc x* function.

[0036] It is possible to determine the actual peak of the *sinc x* function using a *sinc x* reconstruction filter. However, such a filter requires a large number of samples for accurate reconstruction. It may be possible to produce a reasonable result with samples of approximately twenty chips to generate a minimally acceptable result. However, such a process is time-consuming and computationally difficult. More conventional searchers simply look for the peak energy at a sampled data point and presume the actual peak to coincide with the sampled data point.

[0037] The accuracy of peak location by a conventional searcher is limited by the amount (measured in chips) that the stored reference code is shifted by the search

process. In the example illustrated in FIG. 3, the searcher shifts the PN code one chip at a time. As a result, the accuracy of peak determination is limited to one-half that amount (*i.e.*, ± ½ chip). For example, the actual peak correlation value may be at a point **142**, illustrated in FIG. 3 as occurring just past 1½ chips. Because the

5 conventional searcher only shifts the PN code by one chip at a time, the conventional searcher would still determine the peak to be located at two chips rather than at the actual peak **142**. Similarly, the actual peak may be delayed and occur at a point **144**. Again, because of the limitation in measurement, the conventional searcher would indicate the peak as occurring at two chips rather than 2.4 chips.

10 **[0038]** Thus, the actual peak may occur somewhere between 1½ chips and 2½ chips. If the actual peak was at a location greater than 2½ chips, the value measured at chip **3** would exceed that of chip **2** and thus the *sinc x* function would have a peak located at chip **3**. Therefore, if the searcher uses one-step increments, the resolution is limited to ½ chip. As noted above, the increment size (in chips) can be made arbitrarily small, but

15 with the resultant increase in acquisition time since the searcher must perform significantly more calculations.

[0039] A one-chip increment may be satisfactory for some CDMA systems. However, greater reliability is achieved when the system **100** uses ½-chip increments. That is, the conventional searcher shifts the stored PN code ½-chip at a time and performs correlation

20 analysis. This is illustrated in the waveform of FIG. 4 where a correlation waveform **150** is centered at chip **2**. That is, the maximum numeric value was detected by the conventional searcher at chip **2**. As discussed above, the resolution of the search process is limited to ± ¼-chip when using a ½-chip increment in the PN code. Thus, the actual peak may be as early as 1.75 chips, as indicated by reference numeral **152** or as late as

25 2.25 chips, as indicated by a reference numeral **154**. In either case, the conventional searcher will indicate the peak occurring at two chips since the resolution of the conventional searcher in this example is limited to ± ¼ chip.

[0040] As can be appreciated, other resolutions may be used to determine the correlation peak with the desired level of accuracy. For typical CDMA voice

30 communications, ±1/4-chip resolution is generally sufficient. However, ±1/4-chip

resolution provides unsatisfactory results for position location. Based on radio signal propagation measurements, ±1/4-chip resolution translates into a possible error of ± 60 meters when determining the distance from a particular BTS. When one considers that distances from multiple BTSs (*e.g.*, the BTSs **12-18** of FIG. 1) must be determined, a

5   ± 60-meter error in each distance measurement results in an unacceptable degree of inaccuracy for position determination.

[0041] The present invention provides accurate time of arrival data without the need for a *sinc x* reconstruction filter and the accompanying extensive processing associated therewith. As will be discussed in more detail below, the searcher **116** (see FIG. 2)

10   calculates correlation values. The signal analyzer **120** uses a small number of correlation values and the mathematical model **122** to accurately determine the TOA.

[0042] The searcher **116** (see FIG. 2) calculates a correlation value every 1/2-chip, resulting in a resolution of ±1/4 chip. The output of the searcher **116** is a value indicative of the received signal strength at each particular ½ chip interval. The signal

15   strength value is sometimes referred to as a received signal strength index (RSSI), as is known in the industry. However, as noted above, other measures may be used for the correlation value and generated by the searcher **116**.

[0043] In a conventional embodiment, the time of arrival is generally determined to be the time offset of the correlation value having the maximum RSSI. However, as noted

20   above, the actual peak may occur in-between the particular points in time at which measurements are taken. That is, the actual peak value may fall between the 1/2-chip intervals used by the searcher **116**. It is possible to use the various RSSI values at each of the ½ chip intervals and fit them to a curve corresponding to the *sinc x* function. However, such curve fitting is a burdensome task that cannot be readily done with the

25   limited computing power available in the typical wireless device **10**. Furthermore, even with a more powerful processor, the time-consuming task of curve fitting cannot be readily done in real time to provide the desired results.

[0044] The system **100** uses the mathematical model **122** to simulate the general curve of the *sinc x* function. The shape of the curve and the actual peak can be readily

determined using a relatively low number of sample points. In one embodiment, the *sinc x* function is modeled by a simple quadratic function having the form:

$$y(x) = ax^2 + bx + c \qquad (2)$$

where $y(x)$ equals the correlation output value (*e.g.*, RSSI) as a function of x, x equals a time offset, and a, b, and c are coefficients. The coefficients a, b, and c may be readily determined using the correlation values at three sample points. The first sample point is the time offset at which the maximum signal level was detected. This is sometimes referred to as the "on-time" energy value and may be mathematically referred to with respect to equation (2) above as $y(0)$. The two remaining values are the correlation values at adjacent sample points. In the example above wherein the searcher **116** searches at ½-chip increments, the correlation value at ½ chip before the on-time value and ½ chip after the on-time value are used to determine the coefficients a, b, and c. These may be referred to as the "early" energy value and a "late" energy value and are referred to with respect to equation (2) above as $y(-0.5)$ and $y(0.5)$, respectively.

[0045] The coefficients a, b, and c may be readily determined using the following:

$$a = 2y(0.5) + 2y(-0.5) - 4y(0) \qquad (3);$$

$$b = y(0.5) - y(-0.5) \qquad (4);$$

and

$$c = y(0) \qquad (5).$$

The modeling of the *sinc x* function by quadratic equation is illustrated in the waveform of FIG. 5 where the maximum correlation value (*e.g.*, RSSI) was detected at chip 2 and is indicated by a reference numeral **160**. The correlation value for the early energy value (*i.e.*, at 1½ chips) is indicated by a reference numeral **162**, while the correlation value for the late energy value (*i.e.*, at chip 2.5) is indicated by a reference numeral **164**. The correlation values at the points **160-164** may be inserted in

equations (3)-(5) above to determine the values for the coefficients a, b, c. Looking at the wave form of FIG. 5, it is possible to determine that the peak value is somewhere between chip 2 and 2.5. However, it is possible to determine the exact location of the peak using simple mathematics. Equation (2) is a simple quadratic equation whose

5 derivative may be expressed by

$$y'(x) = 2ax + b \qquad (6).$$

The slope of the equation is equal to zero at the peak. By setting equation (6) to zero, we may solve for x and find that:

$$x = \frac{-b}{2a} \qquad (7).$$

10 Thus, the peak may be readily determined by calculating the coefficients a and b.

[0046] The process described above is relatively simple as compared with the process of curve fitting to the *sinc x* function. Once the coefficients a and b are determined, the location of the actual peak of the curve may be readily determined using simple division operation. As is known in the art, a division operation is generally simple for a

15 microprocessor, but can be more difficult to execute in a DSP. As an alternative to the calculation of equation (7), it is possible to determine the peak position using an iterative technique. The advantage of an iterative technique is that it avoids the necessity of performing a division operation. A simple example algorithm for determining the position of a peak based on three data sample points (*i.e.*, the early

20 energy correlation value, the on time energy correlation value, and the late energy correlation value).

```
/* Input energies given by early, ontime, and late */
e1 = early + late - 2*ontime;
e2 = late - early;
compare = e1 + (2^(m-1))*abs(e2);
relative_position = 0;
while ( compare >=0 )
{
    relative_position += 1/(2^m);
    compare += 2*e1;
}
relative_position *= sign(e2);
```

[0047] The algorithm illustrated above is generalized to a resolution of $\dfrac{1}{2^m}$ chips. The simplified implementation is ideal for fixed-point processors, and is based on the second order approximation of the received pulse shape.

[0048] In most applications, the second order model of equation (2) is generally satisfactory for determining the time of arrival and provides an acceptable degree of accuracy in determining the position of the wireless unit **10** (see FIG. 1) using conventional AFLT techniques. However, if greater accuracy is desired, it is possible to provide a higher order mathematical model to simulate the *sinc x* function. For example, a third order equation may more closely model the desired function. Those skilled in the art will recognize that high order functions will require a greater number of sample points in order to determine the coefficients. However, the mathematical modeling of the *sinc x* function may still be performed more efficiently by the present invention than by a *sinc x* reconstruction filter. The principles of the present invention may be generalized to third order or any other higher order model. As noted above, the second order function is selected as a trade-off between accuracy and processing time. However, these processes are more efficient than curve fitting a number of data points to the *sinc x* function. It should be noted that, in the case of a quadratic equation, the three calculated data points (*i.e.*, the early energy value, the on-time energy value, and the late energy value) all intersect with the actual *sinc x* function and thus provide an acceptable degree of accuracy in determining the precise location of the peak.

[0049] The operation of the system **100** is illustrated in the flow chart of FIG. 6 where at a start **200**, the wireless unit **10** is under power. In step **202**, the system **100**

calculates correlation value. As is known in the art and discussed briefly above,the correlation value may be indicated by many different types of measurements, such as total energy, pilot energy per PN chip, RSSI, or the like. The wireless unit **10** compares a stored PN code with a PN code received by the receiver **110** (see FIG. 2). If the PN

5   codes match, a relatively high correlation value will be calculated in step **202**. The system **100** stores the calculated correlation value in step **206** and moves to step **210** to shift the PN code. As previously discussed, the PN code may be shifted in any desirable increment of chips. For example, it is common to shift the PN code ½-chip at a time across a range of PN values.

10   [0050] In decision **212**, the system determines whether the shifted PN code is at the end of the range of PN values. If the shifted PN is not at the end of the range of PN values, the result of decision **212** is NO. In that case, the system returns to step **202** to calculate a new correlation value for the shifted PN code. If the shifted PN code is at the end of the acceptable range of PN values, the result of decision **212** is YES. In that event, in

15   step **214**, the system **100** analyzes the stored correlation values to find the chip with the maximum correlation value.

[0051] In step **216**, the system **100** uses the predetermined mathematical model **122** (see FIG. 2) to determine coefficients using the maximum correlation value and correlation values at one or more adjacent measurement intervals in either direction. In

20   an exemplary embodiment, the mathematical model is a quadratic function having three coefficients (*i.e.*, *a*, *b*, and *c*). The three coefficients may be readily determined using the maximum correlation value and correlation values at adjacent measurement points, such as, by way of example, ½-chip before the maximum (*i.e.*, the early energy value) and ½-chip after the maximum (*i.e.*, the late energy value).

25   [0052] In step **220**, the system **100** determines the peak location with the desired degree of accuracy. As noted above, the actual peak value may be calculated analytically using, by way of example, the mathematical formula of equation (7). Alternatively, the peak location may be determined in an iterative process, such as described above. The process ends at **222** with the peak location having been determined to the desired degree

30   of accuracy.

[0053] With accurate time of arrival data, it is possible to accurately determine the location of the wireless unit **10**. The actual process of determining location using AFLT is known in the art and need not be described herein. However, it follows that the accurate time of arrival data provided by the system **100** results in a more accurate

5   calculation of the location of the wireless unit.

[0054] It is to be understood that even though various embodiments and advantages of the present invention have been set forth in the foregoing description, the above disclosure is illustrative only, and changes may be made in detail, that remain within the broad principles of the invention. Therefore, the present invention is to be limited only

10   by the appended claims.